COMPARISONS OF CUMULUS PARAMETERIZATION SCHEMES AND ENSEMBLE FORECASTING

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1. INTRODUCTION

Precipitation is one of the most difficult parameters to forecast in numerical weather prediction (NWP). Despite substantial reductions in forecast errors for wind, temperature, sea level pressure, and geopotential heights as model improves, progress in precipitation forecast has been slow (Olson et al. 1995). One of the problems involves the representation of subgrid-scale convection and precipitation process, or the cumulus parameterization, in a NWP model. Many cumulus parameterization schemes (CPSs) have been developed and implemented into NWP models. However, most of CPSs are developed in specific convective environments and are evaluated in a limited number of cases (Yang et al. 2000). None of CPSs are specifically designed for the precipitating systems in the East Asia, or the Taiwan area in particular. Therefore, the first part of this paper presents a comparison study of a few CPSs for the heavy rainfall events in Taiwan.

Wang and Seaman (1997) performed a comparison study of four CPSs, the Anthes-Kuo, Betts-Miller, Grell, and Kain-Fritsch schemes, using the Penn State/NCAR MM5 model. Performance of these CPSs was examined using six precipitation events over the continental United States for both cold and warm seasons. They found that no one CPS always outperformed the others. The general 6-h precipitation forecast skill for these schemes was fairly good in predicting four out of six cases examined in the study, even for higher threshold. The forecast skill was generally higher for cold-season events than for warm-season events. There was an increase in the forecast skill with the increase of horizontal resolution, and the gain was most obvious in predicting heavier rainfall amounts.

This first part of this study follows Wang and Seaman (1997) to evaluate the performance of four CPSs in the MM5 model, using six rainfall events in four seasons over the Taiwan area. Precipitation forecast is then evaluated statistically over the MM5 grid points in the Taiwan area using the threat score and bias score for different threshold values based on island-wide raingauge observations.

2. METHODOLOGY

The PSU-NCAR mesoscle model MM5 Version 2.11 is used in the first part of this study. The MM5 model is run at grid sizes of 45 and 15 km. The four CPSs chosen for evaluation are the Anthes-Kuo scheme (AK; Anthes 1977), the Betts-Miller scheme (BM; Betts and Miller 1993), the Grell scheme (GR; Grell 1993), and the Kain-Fritsch scheme (KF; Kain and Fritsch 1993). All four CPSs examined are the default versions that are implemented in the standard MM5. An ensemble forecast (AG) is also made by arithmetically averaging the rainfall forecasts by four CPSs.

The observations used to assess MM5 predictions are the hourly reports collected by the automatic raingauge stations at the Central Weather Bureau in Taiwan. This dataset consists of 343 stations around the Taiwan island with an average distance less than 5 km (Fig. 1). The raingauge rainfall data are then interpolated to the 15-km MM5 grid points (155 points totally), using the Cressman (1959) objective analysis method with a radius of influence of 8.46 km.

Evaluation of the precipitation predictions focuses on the rainfall area and rainfall amount. For precipitation area forecast, rainfall forecast of the 15-km MM5 by each CPS experiment is compared to the "observed" rainfall (after objective analysis) and are evaluated quantitatively using statistical skill scores like the threat and bias scores (Anthes 1983) for several threshold values (at 0.25, 2.5, 10, 15, 20, and 25 mm). For precipitation amount forecast, the following statistical parameters are examined: mean error, mean absolute error, mean error percentage, mean absolute error percentage, precipitation

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summary percentage, and precipitation maximum percentage.

3. CASES AND MODEL

We select six cases that represent a variety of synoptic and mesoscale weather conditions producing heavy rainfalls over the Taiwan area. These six cases include the events of spring rainfall (18 Feb. 1999), summer-time thunderstorm (27 Aug. 1999), winter cold-air outbreak (11 Jan. 1999), autumn cold front (6 Oct. 1998), Typhoon Otto (4 Aug. 1998), and Mei-Yu front (27 May 1999).

The numerical model used in the first part of this study is the Penn State/NCAR non-hydrostatic model MM5 (Grell et al. 1994) Version 2.11. The MM5 is a three-dimensional, limited-area, primitive-equation, nested-grid model with a terrain following σ (non-dimensional pressure) vertical coordinate. The MM5 physical parameterizations used in this study include the Blackadar (1979) planetary boundary layer scheme, the radiation scheme with the interaction between clear sky and clouds (Dudhia 1989), the grid-scale Simple Ice (Dudhia 1989) microphysics scheme, and the subgrid-scale cumulus parameterization. The model configuration includes a coarse mesh of 45-km grid size and a fine mesh of 15-km grid size. Domain size is 81×71 for coarse mesh and 91×91 for fine mesh, with 27 σ-levels in the vertical. Each MM5 run is 36 hours. The initial condition is provided by the analysis field of the Central Weather Bureau Global Forecast System (CWBGFS; Liou et al. 1997), and the boundary condition is provided by the CWBGFS forecast field. Surface observations and sounding data are included through the MM5 objective analysis package (RAWINS) to improve the initial condition field.

4. RESULTS FROM CPS COMPARISONS

Principal findings for rainfall area prediction are summarized here:

1). Besides the warm-season events (spring rainfall and summer-time thunderstorm), the 6-h precipitation forecast from the four CPSs in the 15-km MM5 is fairly good (TSs > 0.4) in predicting rainfall systems in Taiwan (Figure 2).
2). The forecast skill is generally higher for cold-season events (autumn cold front and winter cold-air outbreak) than for warm-season events (spring rainfall and summer-time thunderstorm).
3). The predictive skill for each CPS has a large case-to-case variation in all six events, and none of the CPS consistently outperforms the others in all evaluation parameters.
4). Besides the warm-season events (spring rainfall and summer-time thunderstorm), the ensemble forecast has the best skill in predicting the occurrence of rainfall (i.e., using a threshold of 0.25 mm).

Similarly, principal findings for rainfall amount prediction are summarized here:

1). Besides the spring rainfall case, all CPSs underpredict the rainfall amount, especially for heavy rainfall events (Mei-Yu front and Typhoon Otto).
2). Among all six cases, the Anthes-Kuo (AK) scheme has the most false-rainfall points and the Betts-Miller (BM) scheme has the least false-rainfall points.
3). For total precipitation volume prediction, the Grell (GR) scheme has the best forecast skill in predicting four out of six rainfall events.
4). For precipitation maximum prediction, the Betts-Miller (BM) scheme has the best forecast score in predicting three out of six rainfall events.

5. ENSEMBLE FORECAST WITH MIXED CPS

Du et al. (1997) examined the uncertainities of initial condition and CPS on quantitative precipitation forecasts (QPFs) for a cyclogenesis case in the United States using the Penn State/NCAR MM4 model. Ensemble QPF had large sensitivity to initial condition uncertainties. Ensemble averaging reduced the root-mean-square error for QPF and nearly 90% of QPF improvement was obtained using ensemble sizes as small as 8-10. Further sensitivity experiments showed that the QPF improvement by ensemble forecasting exceeded the improvement by doubling horizontal resolution.

Mullen et al. (1999) investigated the impact of differences in analysis-forecast systems on dispersion of an ensemble forecast for a cyclogenesis case. Error growth by initial condition uncertainities significantly depended on the analysis-forecast system. QPFs and probabilistic QPFs were extremely sensitive to the choice of CPS in the model, similar to the findings of Yang et al. (2000) for a Mei-Yu frontal precipitation event. Therefore, the combined effect of uncertainties in precipitation physics and the initial conditions provides a means to increase the dispersion of QPF ensemble forecast system. The second part of this paper describes Ensemble Forecast Experiments we conducted during the Mei-Yu season in 2000 and 2001 and also some preliminary results.

6. ENSEMBLE FORECAST EXPERIMENT IN THE MEI-YU SEASON

Based on the concept of ensemble forecasting discussed above, scientists at several universities and operational centers in Taiwan jointed together to conduct the Ensemble Forecast Experiment during the Mei-Yu season (May and June) in Year 2000 and 2001. The participating sites in Taiwan included National Taiwan University (NTU), National Central University (NCU), National Taiwan Normal University (NTNU), Chinese Culture University

(CCU), Central Weather Bureau (CWB), and Civil Aeronautics Administration (CAA). Each site used the Penn State/NCAR MM5 (Grell et al. 1994) Version 3.3 as a common model with different precipitation (cumulus and microphysics) parameterizations at different institute. Table 1 lists the physics schemes used in the MM5 ensemble experiment. In Year 2001, Dr. Jim Bresch at NCAR joined the Ensemble Forecast Experiment and conducted additional four MM5 runs (Set B in Table 1) in order to increase the ensemble spread and test new physics schemes.

The model configuration for the MM5 ensemble forecast experiment includes a coarse mesh of 45-km grid size and a fine mesh of 15-km grid size. Domain size is 81Ⅹ71 for coarse mesh and 79Ⅹ79 for fine mesh, with 23 σ levels in the vertical. Each MM5 run is 36 hours. The initial condition for MM5 ensemble is provided by the CWBGFS analysis field as the first-guess field and the boundary condition is provided by the CWBGFS forecast field through the “regrid” package. Surface observations and sounding data are included by objective analysis to improve the first-guess field through the “little-r” package.

During the Mei-Yu seasn (May and June), Miss Hui-Chuan Lin at CAA put the initial-condition and boundary-condition files for the MM5 ensemble runs at a common ftp site (provided by CWB) twice a day (00 UTC and 12 UTC). Each participating site came to this ftp site to obtain files for the MM5 ensemble run. Because of the narrow bandwidth of Taiwan’s educational network, each participating site only ftped the digital 6-hourly rainfall forecast of 15-km MM5 run back to CWB. Dr. Jen-Hsin Teng at CWB then produced ensemble rainfall forecasts to be used by forecasters to assist CWB’s issuing of heavy rainfall warnings in the Mei-Yu season.

7. RESULTS FROM ENSEMBLE FORECASTING

Figure 3a shows the threat score for the 12-24 h forecast for all 6 members of MM5 ensemble runs during the 2000 Mei-Yu season (15 May to 20 June 2000). It included the MM5 runs with both the 00 UTC initializations and 12 UTC initializations. In the figure, the “ensemble-mean forecast” (“Average” curve) was done by simply averaging the rainfall forecasts of 6 MM5 ensemble members. The threat score decreased with the increase of precipitation threshold, consistent with Olson et al. (1995), Chien et al. (2001) and others. It is very clear from Fig. 3a that the ensemble-mean forecast always out-performed individual forecast in all precipitation thresholds. For the lowest threshold (0.25 mm), the threat score of ensemble-mean forecast (Average) had the highest score of 0.39 and the lowest score of ensemble member (NTNU) was 0.32. In other words, the ensemble forecast technique improved the rainfall forecast for lowest threshold (i.e., the possibility for rainfall occurrence) as much as 30%! Figure 3b is the threat score for the 24-36 h forecast for all 6 MM5 ensemble members during the 2000 Mei-Yu season. Similarly, the ensemble-mean forecast apparently out-performed individual forecast and this improvement persisted in all precipitation thresholds.

Finally, NWP model forecasts have inherent limitation due to the uncertainties of initial condition and physical parameterization. Taiwan’s steep mountain and rich weather phenomena (Mei-Yu front, typhoon, winter-time cold front, summer-time afternoon thunderstorm and local circulation) make the NWP limitation more severe. In order to reduce the impact of uncertainties of initial condition and physical parameterization on NWP performance, ensemble forecasting should be one way to enhance the NWP value and extend its predictability.

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Table 1: Physics schems of MM5 Ensemble members on the 45-km/15-km nested grid.

Site	Cumulus scheme	Microphysics scheme	PBL scheme
	Set A with the first guess from the CWB Global Model		
NTU	Grell	Resiner 1	MRF
NCU	Betts-Miller	Resiner 1	MRF
NTNU	Kain-Fritsch	Simple Ice	MRF
CCU	Kain-Fritsch	Goddard	MRF
CWB	Anthes-Kuo	Simple Ice	MRF
CAA	Kain-Fritsch	Reisner 1	MRF
	Set B with the first guess from the NCEP AVN Global Model		
NCAR1	new Kain-Fritsch	Schultz	MRF
NCAR2	Grell	Schultz	MRF
NCAR3	new Kain-Fritsch	Schultz	Eta
NCAR4	new Kain-Fritsch	Reisner 1	MRF

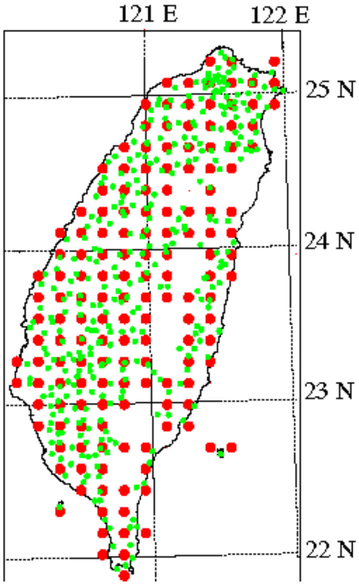


Figure 1: Rain gauge stations (small dots) and the 15-km MM5 grid points (big dots) over the Taiwan area.

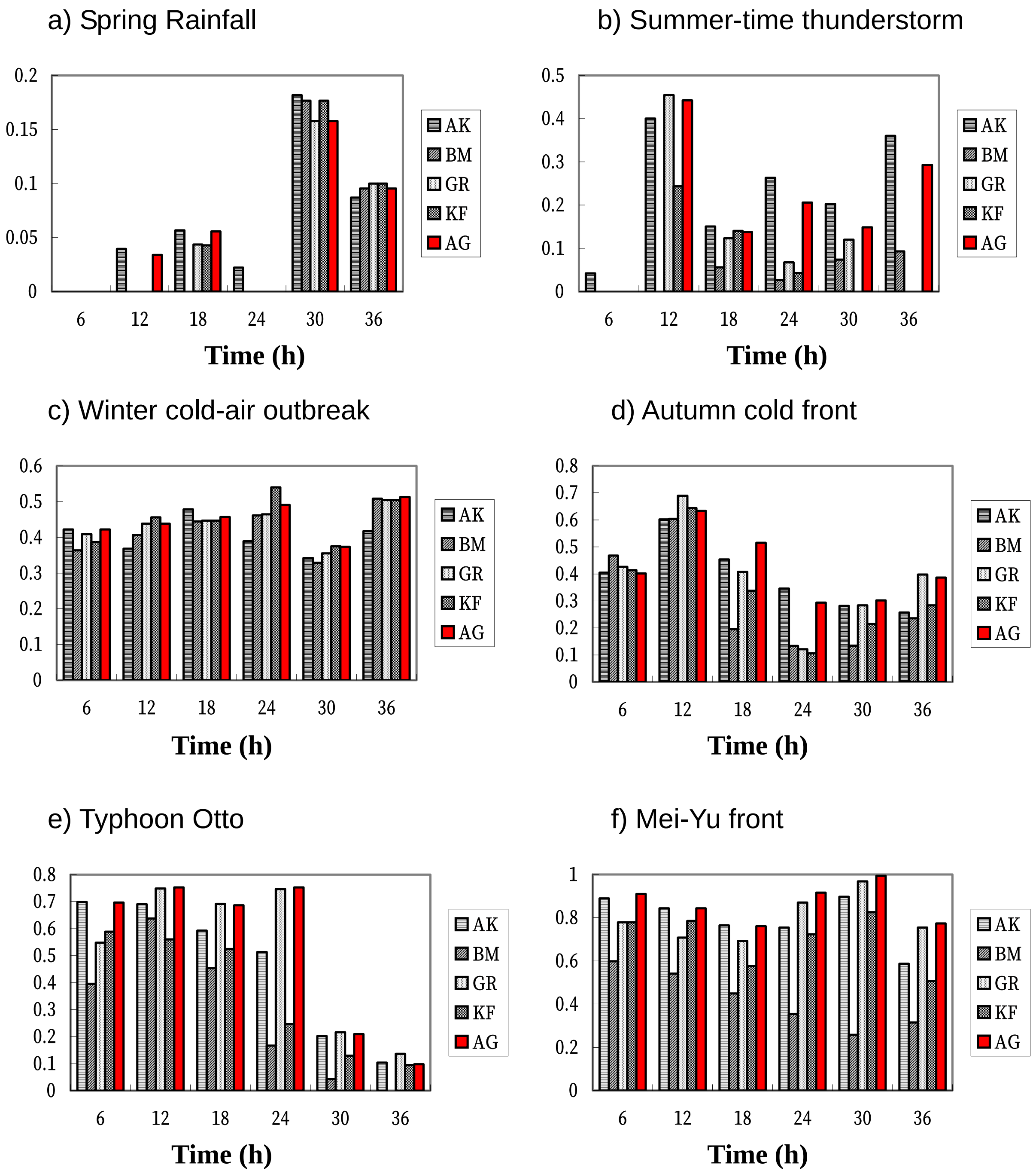
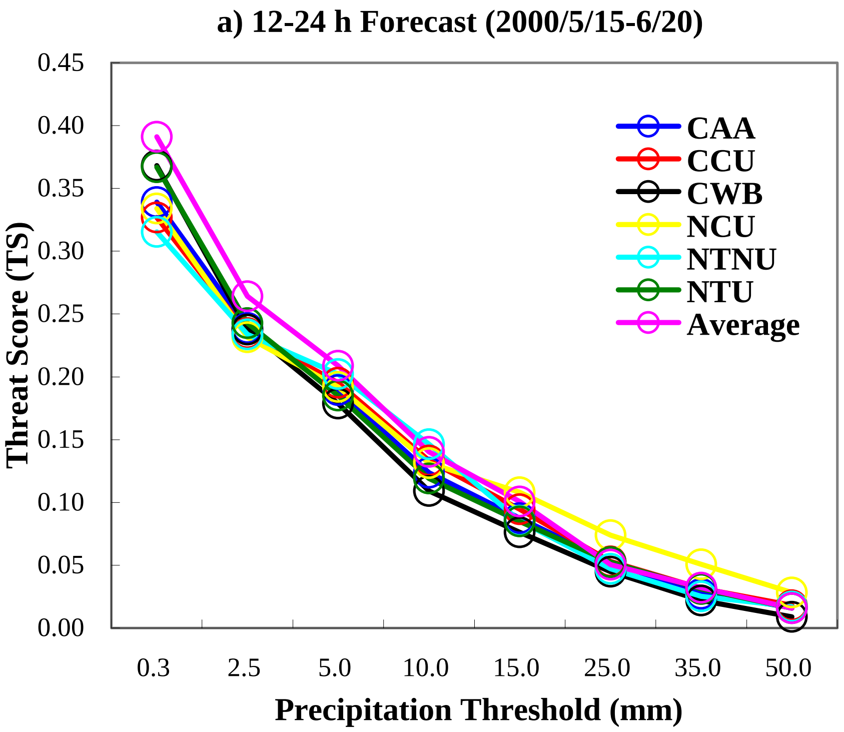
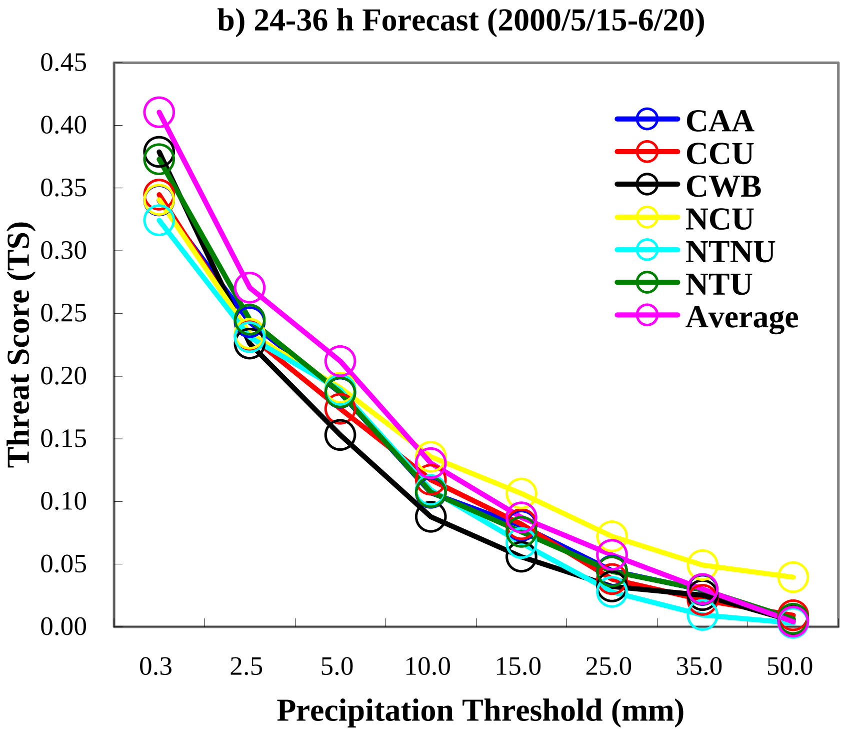


Figure 2: Threat scores (TSs) at the 0.25 mm threshold for 6-h rainfall predictions from 15-km MM5 runs for the a) spring rainfall, b) summer-time thunderstorm, c) winter cold-air outbreak, d) autumn cold front, e) Typhoon Otto, and e) Mei-Yu front case. The times on the abscissa are relative to the model initial time.



a) 12-24 h Forecast (2000/5/15-6/20)



b) 24-36 h Forecast (2000/5/15-6/20)

Figure 3: Threat scores (TSs) of the MM5 Ensemble Forecast during the 2000 Mei-Yu Season: (a) 12-24 h forecast, and (b) 24-36h forecast.